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CYCLOTRON PROGRAM AT Y-12

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A Speech Presented at  
Oak Ridge Physics Seminar  
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Y-12 AREA

Operated by

CARBIDE AND CARBON CHEMICALS DIVISION  
UNION CARBIDE AND CARBON CORPORATION

Oak Ridge, Tennessee

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Particle Accelerators

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## I

It was just twenty years ago that the principle of "magnetic resonance acceleration" was first proposed by E. O. Lawrence\*. Several years later, after numerous successful experiments, the name "cyclotron" was chosen to designate an accelerator in which the ions were spiraled out to high energies using a large number of successive properly synchronized small electrical impulses. Since that time the cyclotron has become a by-word in nuclear laboratories, and large numbers of these machines have been constructed.

A tabulation a year or so ago showed that there were 18 constant frequency cyclotrons in operation in this country and 11 in foreign countries including France, Germany, Great Britain, Russia, Sweden, and Switzerland. In addition there were three new machines of this type being built in the United States and three in foreign countries. Besides these 35 constant frequency cyclotrons, there were in the United States three synchro-cyclotrons, sometimes called frequency modulated cyclotrons; there were five others being built in this country and four in foreign countries. Also, it should be mentioned that three enormous proton-synchrotrons are being built in this country. The numerous betatron and electron-synchrotron installations have been omitted here in the interest of brevity. The present discussion is to describe the first cyclotron to be installed in the South East (east of the Mississippi and south of the Ohio) now being designed and erected in the Y-12 Area of the Oak Ridge National Laboratory.

## II

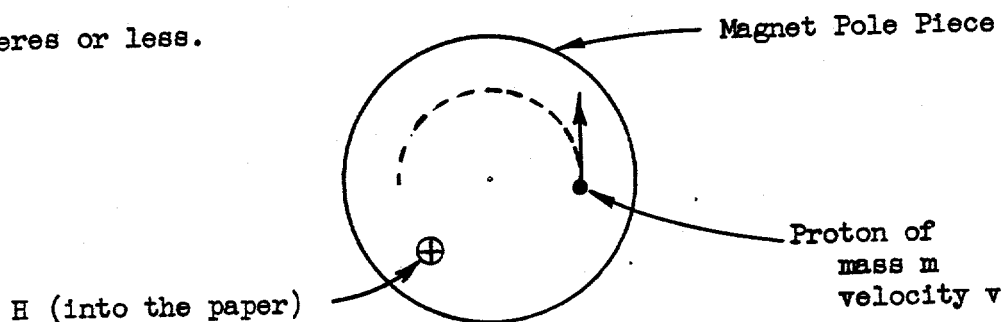
While the basic principals of magnetic resonance accelerators are not complicated, the large number of different types of machines may easily lead to confusion. I would like to ask the indulgence of those already familiar

\* Lawrence, Ernest O. and Edlefsen, N. E., "On the Production of High Speed Protons", Meeting of the National Academy of Sciences, University of California, September 18-23, 1930, Science, 72, 276, 1930.

with the various accelerators while I briefly review some of the basic differences in these machines. Magnetic resonance accelerators fall naturally into four basic groups.

### Fixed Frequency Cyclotron

In this group, a steady magnetic field of from 7000 to 20,000 oersteds is used. The frequency of the applied rf power is constant. Energies up to 20 Mev (Deuterons) have been obtained. Currents usually have been 100 micro-amperes or less.



In the above sketch one may consider the forces on a hydrogen ion. If one equates the magnetic force  $Hev/c$  with the acceleration times the mass of the particle, one may write the equation

$$(1) \quad Hev/c = mv^2/r = m\omega^2 r$$

as  $\omega$  equals  $v/r$  equals  $2\pi f$ , substituting in equation (1)

$$(2) \quad He(\omega r)/c = m\omega^2 r$$

Transposing, one obtains

$$(3) \quad \omega = eH/mc$$

Or

$$(4) \quad f = eH/2\pi mc$$

The important result which may be seen in these equations is of course that the transit time of an ion is not dependent on its radius. Consequently, it may stay in resonance through perhaps several hundred revolutions.

### Synchro-cyclotron

Above 10 Mev the effect of relativity (the increase in weight of

the ions) begins to become important and equation 3 above is no longer exactly true.  $W$  is a function of the mass, which changes at velocities which are appreciable with respect to the velocity of light. To compensate for this effect, which causes the particle to move too slowly for the radio frequency and to get behind in phase, the oscillator frequency is varied at the proper rate to just compensate for the increasing mass of the ion. Hence the machine is called a frequency modulated cyclotron or synchro-cyclotron.

Theoretically it would be possible to vary the magnetic field with time, rather than the frequency. Practically, it has proven more advantageous to vary the frequency. The magnetic field in this type of machine is in the range from 15,000 to 20,000 oersteds and of course must cover a larger area than in constant frequency machines because the particles may go now to energies as high as 350 million volts or perhaps higher. The cost of construction of magnets and other components begins to become excessive as one goes beyond this range. Maximum currents obtained are usually of the order of 0.1 to 1.0  $\mu$ a, time average.

#### Betatron and Synchrotron

These are devices not for the acceleration of heavy ions but for electrons and therefore will be omitted from this discussion except to account for their place in the general accelerator groups.

#### Proton Synchrotron

The name of this group apparently is not yet settled and is variously called a bevatron, a cosmotron, a cyclodrome, or a proton synchrotron. In my opinion accuracy and logic would favor still a fifth name, proton frequency-modulated synchrotron, which is obviously out of the running because of its length.

This machine is similar to an ordinary fm or synchro-cyclotron in all



respects except one. The ion does not spiral out as in the other type accelerators but stays in a fixed orbit made possible by a changing magnetic field which is raised in intensity at the proper rate to hold the orbit radius constant as the particle gains energy. This fixed orbit is very important from a practical point of view because it makes possible the construction of doughnut type magnets, 50 to 100 feet in diameter. A conventional magnet of these dimensions would be of questionable feasibility and colossally expensive. Machines of the proton synchrotron variety are expected to reach one billion to several billion electron volts in the not too distant future. Currents expected are very small, of the order of perhaps  $10^{-12}$  amperes.

### III

Before starting a description of the cyclotron which is being erected in Oak Ridge, I would like to point out that this project represents the work of a rather large group of engineers and physicists at the Y-12 Area, and my position today is merely to act as a spokesman for the group. The Oak Ridge cyclotron will be of the first mentioned class, a fixed frequency cyclotron, but it will have important features which distinguish it from any other cyclotron now being built or planned.

It will be designed with the expectation of exceeding the presently obtainable ion currents by a factor of ten or more. If one tabulates the performance of the best operating cyclotron in the country, one obtains a list somewhat as follows:

|                  |                         |                       |
|------------------|-------------------------|-----------------------|
| 20 Mev deuterons | 50 $\mu$ a (deflected)* | Berkeley              |
| 16 Mev deuterons | 200 $\mu$ a "           | Carnegie Institution, |
|                  |                         | Washington, D.C.      |
| 12 Mev deuterons | 400 $\mu$ a (probe)     | St. Louis             |

It is planned that the Oak Ridge cyclotron will product 20 - 25 Mev protons and that the ion currents will be between  $10^3$  and  $10^4$   $\mu$ a (measured on an

\* Estimates (Reported verbally)

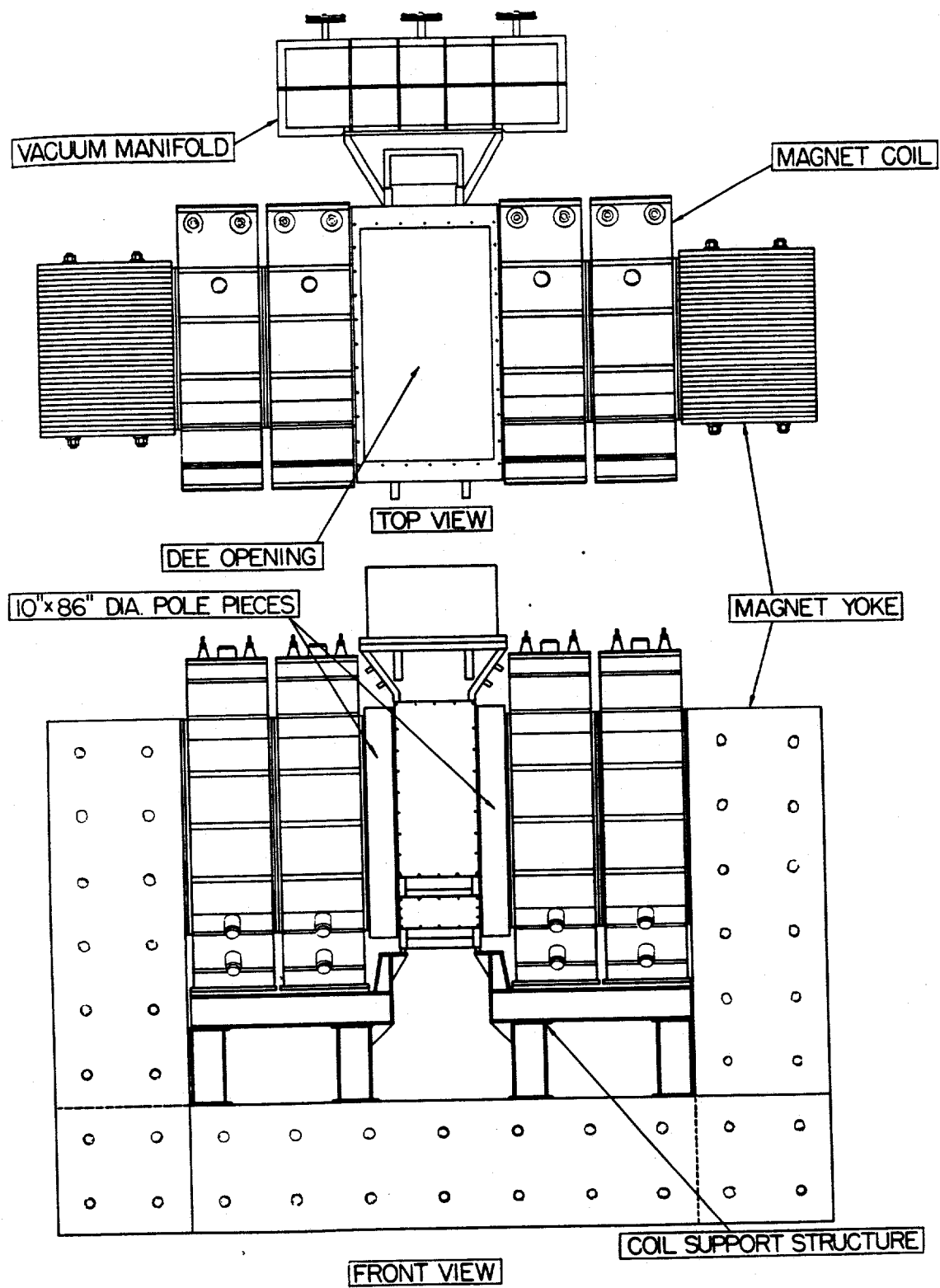
internal target).

One may raise the question, why is this machine designed for protons when most of the other cyclotrons use deuterons. There are several reasons. The required  $H/\rho$  for protons is smaller by a factor proportional to the square root of the mass of the ion. With a given  $H/\rho$  one can always get higher energy protons (double the energy), for the same energy deuterons one must provide 1.4 times the  $H$ . Consider also the nuclear reactions which cannot be obtained readily in a nuclear reactor. These are generally of the type  $(D,n)$ ,  $(D,2n)$ ,  $(D,3n)$ , etc. For the last two the  $(p,n)$ ,  $(p,2n)$  reactions are exactly equivalent.  $(D,n)$  reaction are probably not important as they have high cross sections at rather low energies and much smaller cross sections at the higher energies (20 Mev). It will of course be possible to convert this cyclotron to deuterons by use of a new dee assembly, if desired. The energy would be however only one half of that for protons. The dee assembly can be made compact due to the higher frequency and consequently shorter resonant dee lines. This favors a system where units can be handled and interchanged with greater ease than has been customary in the past.

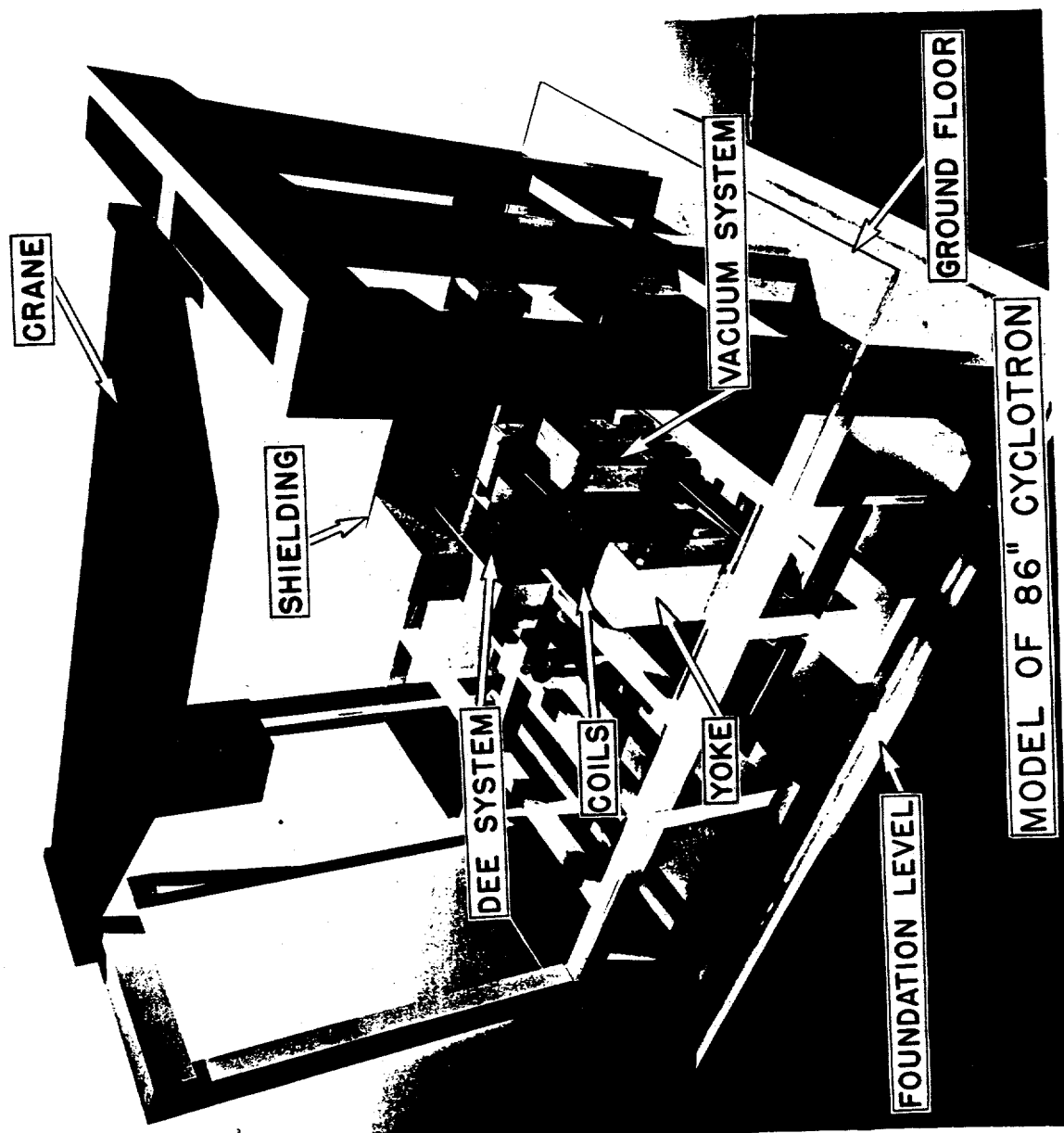
I shall next present a series of slides which will briefly show the basic features of the present design. We shall then come back to consider a number of design problems.

#### Magnet (Slide 1)

It may be seen that the magnet yoke is shaped as a U with the axis of the coils and vacuum tank oriented vertically. The direction of the magnetic field is thus horizontal which puts it at  $90^\circ$  to all conventional cyclotrons. The steel for the yoke is composed of 250 tons of 2" plates bolted together with a large number of  $2\frac{1}{2}$ " tie bars. We believe that a record was set in the erection of this yoke due largely to a careful system which was worked out by the rigging group which did the construction. The total erection time was



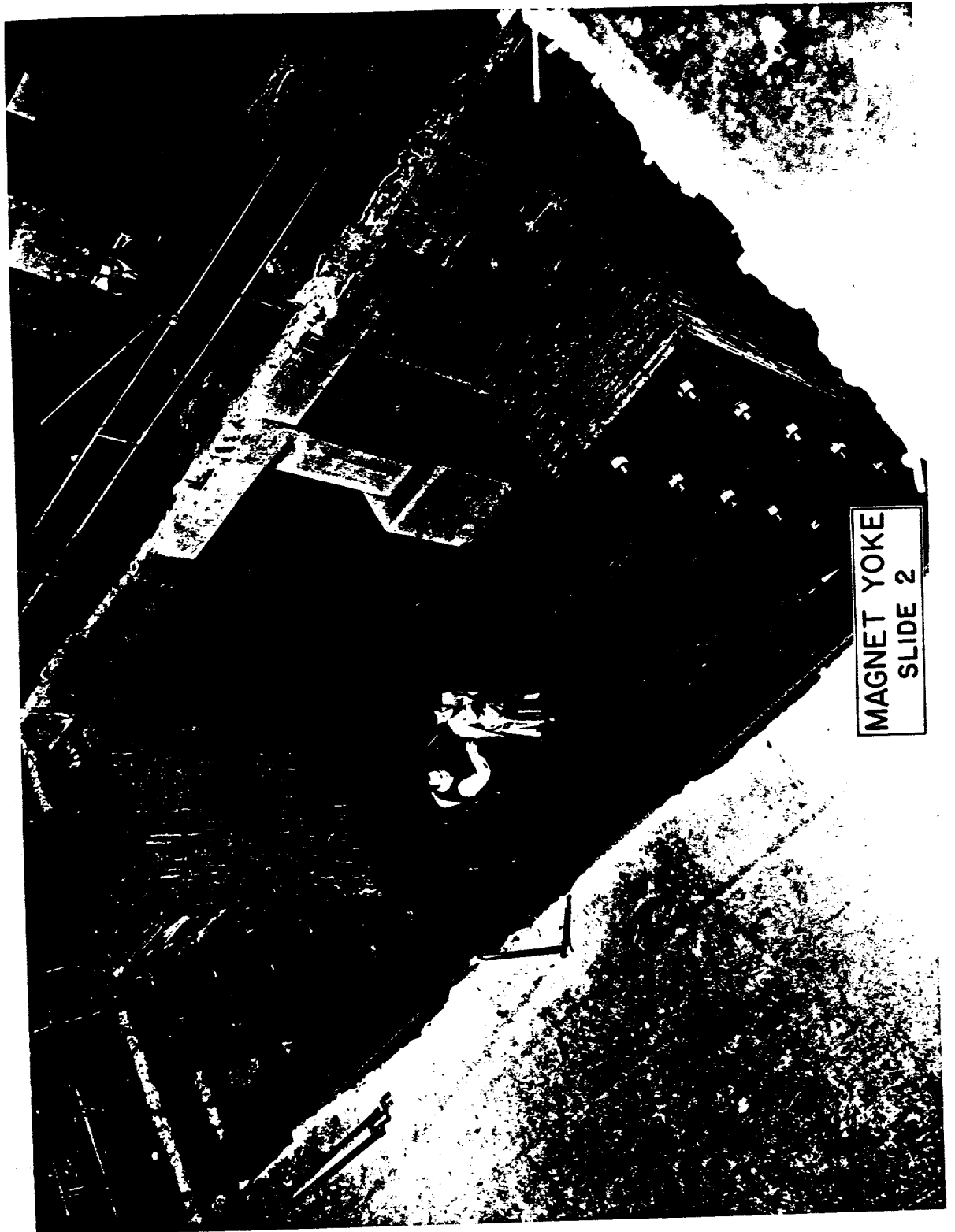
86" CYCLOTRON  
SLIDE 1



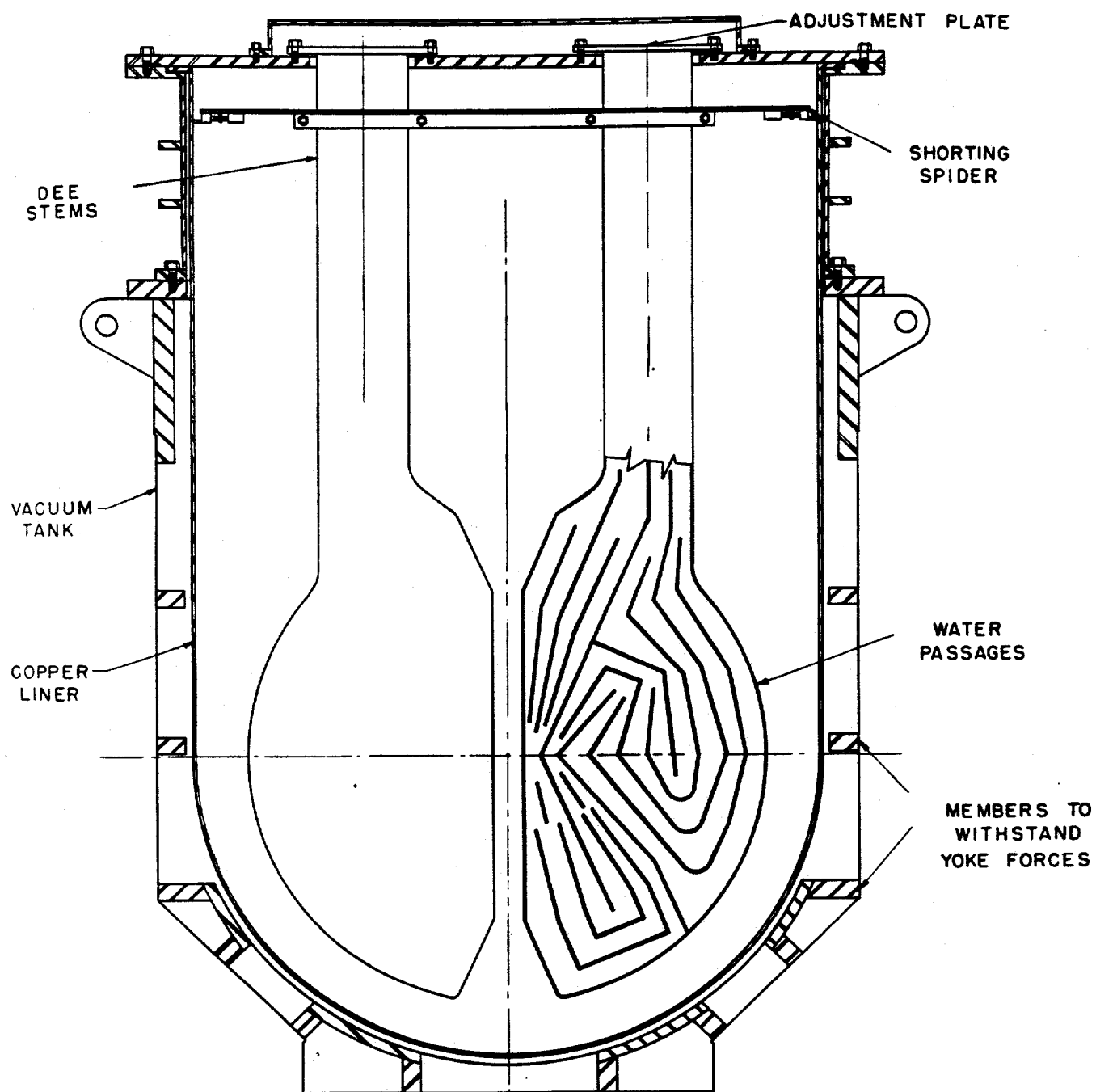
only 25 days from the receipt of the steel until the last bolt was tightened. The diameter of the pole pieces is 86". It will be noticed that the yoke cross section is square; consequently some 16" of circular steel is being provided on each side to adequately smooth out the magnetic field. The steel will consist of two 10" slabs outside of the vacuum tank and the remainder incorporated in the tank walls or inside shims. The vacuum tank is to be an all-welded structure with 4" thick pole pieces and  $1\frac{1}{2}$ " thick stainless steel sides. The force tending to move the two poles together will be several hundred tons. This force will be resisted by a number of heavy members incorporated at the edges of the vacuum tank. The magnetic field is expected to be approximately 9000 oersteds. The connections to the pumping system may also be seen. In the next slide (Slide 2) a photograph of the magnet yoke is shown.

#### Dee System (Slide 3)

The dees are copper pancakes to be brazed together leaving passages for high speed streams of water to remove the large amounts of heat which may be present from the radio frequency power or in the circulating ion beam. Openings at the periphery of the dees will permit fast pumping speed. The dee stems form a quarter wave resonant circuit which is a basic part of the main oscillator. It is to be observed that the dees are removed vertically. This will permit handling radioactive dee assemblies with the crane operator a substantial distance away. The units may then be transferred to caves, where they may cool until they can be safely handled. There is some possibility that with highly focused ion beams from special ion sources, the beam hitting the dees may be much smaller than would be predicted from direct comparisons with other installations. After the removal of an active dee assembly, it is expected that new assemblies can be installed with little loss in time.



MAGNET YOKE  
SLIDE 2



86" CYCLOTRON DEE ASSEMBLY  
SLIDE 3

### Oscillator (Slide 4)

The high frequency generator must be capable of supplying the required power at the resonant frequency of the dee lines. This power is determined primarily by capacitance of the dee electrodes, the radio frequency resistance of the resonant circuit, and the efficiency of energy transfer into the dee system. The dee stems are to be incorporated in an oval, shielded resonant line. The oval shape was selected to give optimum Q, having a lower rf resistance than a rectangular shape. The schematic circuit shows a rather standard ground-grid self-excited oscillator using two Federal F134 tubes in parallel. The coupling of the oscillator to the resonant system is accomplished with half wave length resonant lines, properly terminated in order to maintain the correct magnitude and phase relations between the cathode and the plate voltages. The oscillator is being designed to give 400 kw of rf power at a frequency of 13.4 megacycles.

### Electrical Model (Slide 5)

This photograph shows a full scale electrical model of the cyclotron which has been constructed to provide data on the electrical characteristics of the resonant structure. Measurements are now being made on the dee capacity, the proper length of dee stems, the proper location and length of the transmission line connections and a number of other desired points of information.

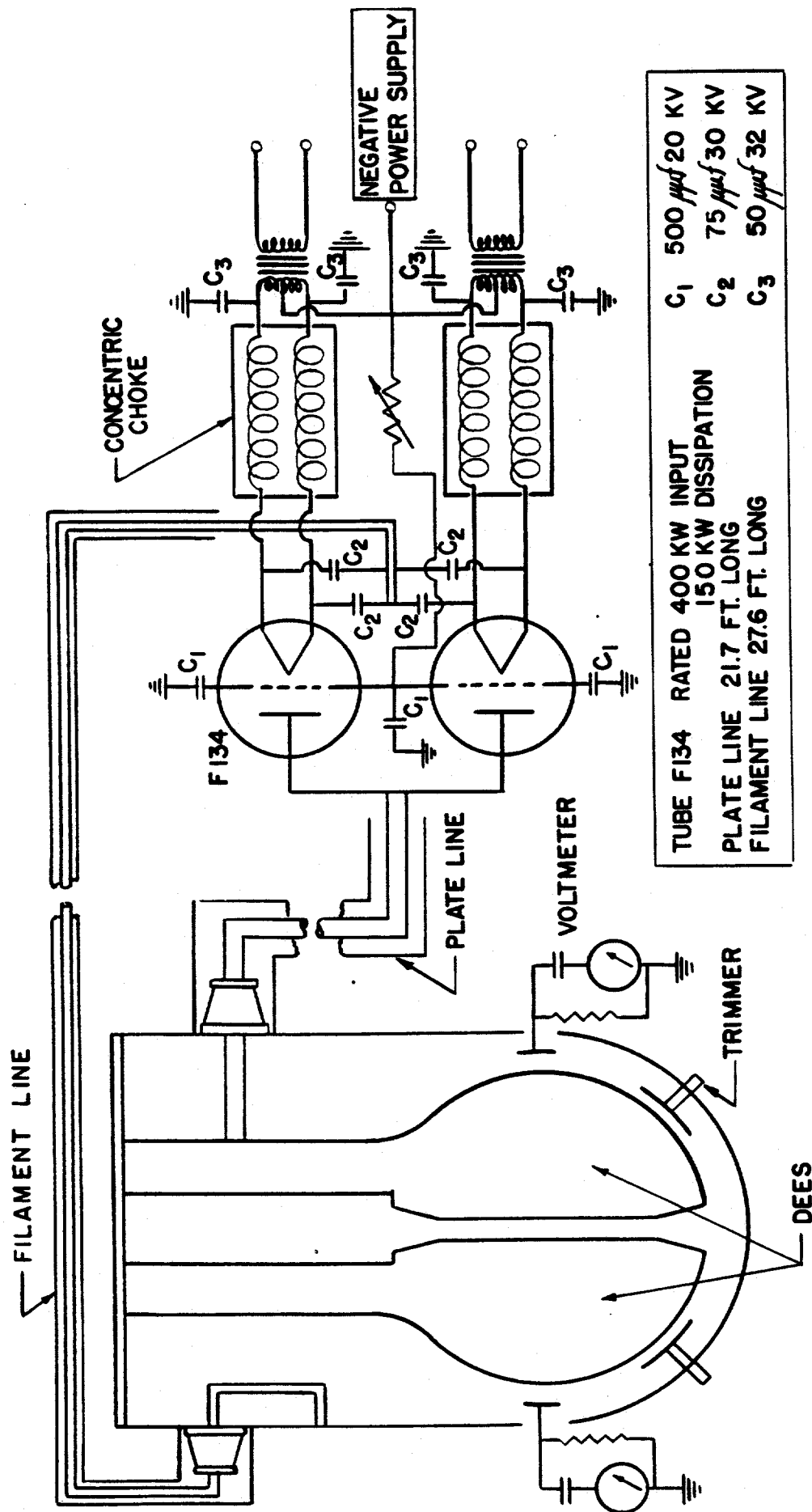
### Specifications

To summarize the characteristics of the Oak Ridge cyclotron one may list the following specifications\*:

|   |                |
|---|----------------|
| Proton Energy   | 25 Mev         |
| Magnetic Field Intensity for Resonance (Non-relativistic) | 8790 Oersteds  |
| Diameter of Maximum Orbit                                 | 66"            |
| Magnetic Gap at Center                                    | 18"            |
| Dee Diameter  | 70"            |
| Clearance from Dee to Liner                               | 4"             |
| Power Losses Unloaded                                     | 150 Kw         |
| Rf Current at Back of Dee Stems                           | 5100 amps, rms |

\*See attached list for more complete specifications.

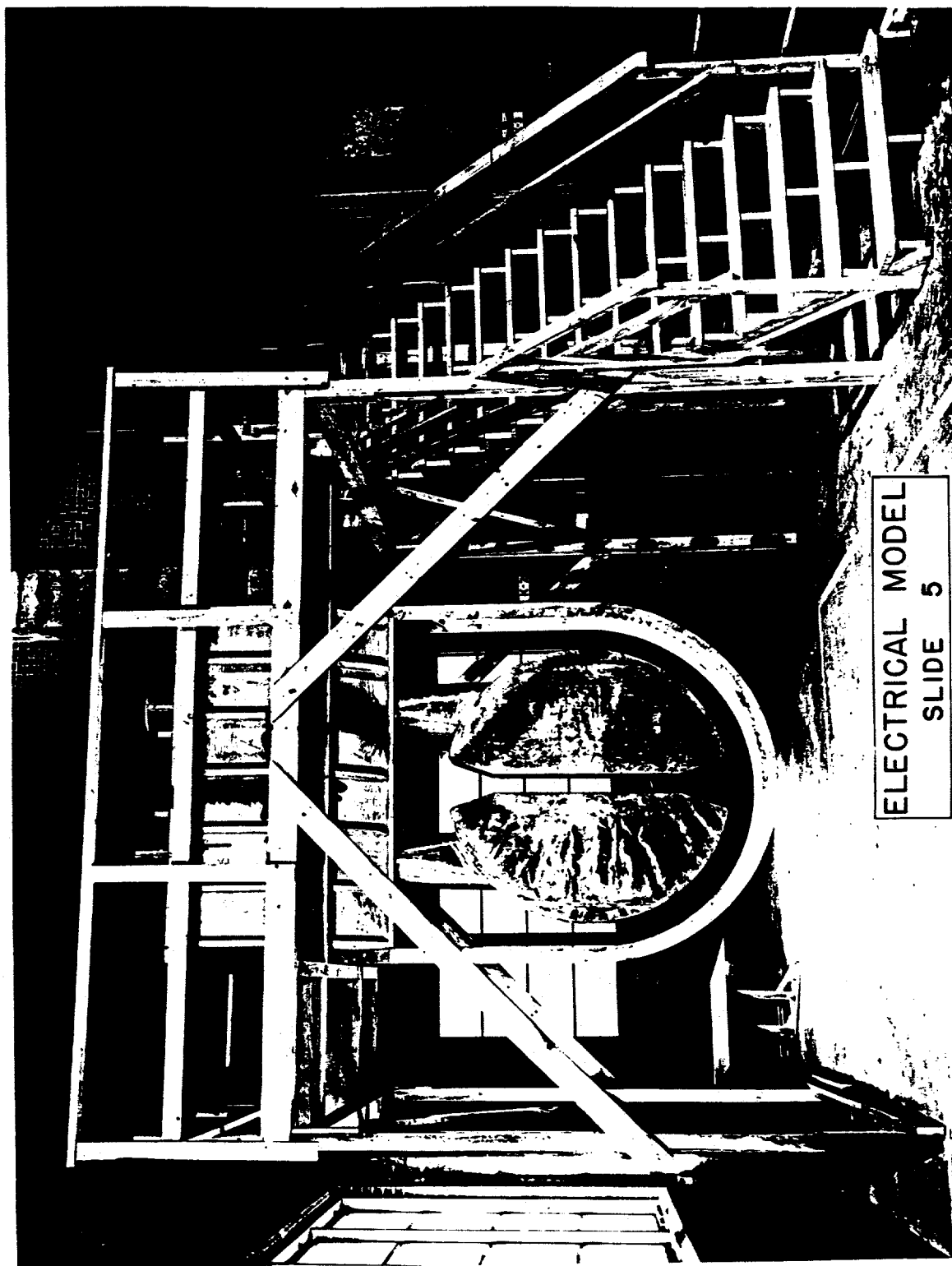




|               |                    |       |                         |
|---------------|--------------------|-------|-------------------------|
| TUBE F134     | RATED 400 KW INPUT | $C_1$ | 500 $\mu\text{f}$ 20 KV |
| PLATE LINE    | 150 KW DISSIPATION | $C_2$ | 75 $\mu\text{f}$ 30 KV  |
| FILAMENT LINE | 21.7 FT. LONG      | $C_3$ | 50 $\mu\text{f}$ 32 KV  |
|               | 27.6 FT. LONG      |       |                         |

86" CYCLOTRON OSCILLATOR

SLIDE 4



ELECTRICAL MODEL  
SLIDE 5

HIGH CURRENT CYCLOTRON SPECIFICATIONS

Revised January 20, 1950

Principle Requirements

|   |             |
|---|-------------|
| Proton Energy (Design) . . . . .                            | 26 Mev      |
| Proton Energy (Desired) . . . . .                           | 25 Mev      |
| Magnetic Field Intensity for Resonance . . . . .            | 8790 Oersts |
| Magnetic Field Intensity Correction at 33" Radius . . . . . | 2%          |
| Resonance Frequency . . . . .                               | 13.4 mc/sec |
| Diameter of Maximum Orbit . . . . .                         | 66"         |
| Magnetic Gap at Center . . . . .                            | 18"         |
| R. F. Peak Voltage of Acceleration (D-to-D) . . . . .       | 500 kv      |
| Beam Current . . . . .                                      | > 1 ma.     |
| Increase in Mass of Protons . . . . .                       | 2.7%        |

Dee System.

|  |                           |
|--|---------------------------|
| D - Diameter . . . . .   | 70"                       |
| D - to - Liner Gap (Flat sides) . . . . .                      | 4"                        |
| D - to - Liner Gap (Side) . . . . .                            | 7"                        |
| D - to - D Gap . . . . .                                       | 4"                        |
| D - to - D Effective Capacity . . . . .                        | $\approx 155 \mu\text{F}$ |
| Length of Oval Shielded Resonant Line . . . . .                | $\approx 5.7 \text{ Ft.}$ |
| O. D. of Inner Conductor . . . . .                             | 12"                       |
| Q Unloaded . . . . .   | $\approx 12,270$          |
| Q Loaded . . . . .   | $\approx 3,680$           |
| Characteristic Impedance of Resonant Line . . . . .            | $\approx 160 \Omega$      |
| R. F. Resistance of Line . . . . .                             | $\approx 0.00375 \Omega$  |
| Power Losses (Total) Unloaded (For Max. Dee Voltage) . . . . . | $\approx 150 \text{ kw}$  |
| Current (For Max. Dee Voltage at Back of Dee Stem) . . . . .   | 5100 amps. rms            |

Oscillator

|                            |  |
|----------------------------|--|
| Circuit . . . . .          | Grounded grid,<br>two tubes in<br>parallel |
| Output (Max. rf) . . . . . | 400 kw                                     |
| Plate voltage . . . . .    | 20 kv                                      |
| Power Triodes . . . . .    | Federal 134                                |

Magnet

|   |                         |
|---|-------------------------|
| Yoke . . . . .                              | "U" Shaped              |
| Yoke Cross section/Coil Core Area . . . . . | 68%                     |
| Yoke Cross section/Pole Area . . . . .      | 53%                     |
| Pole Diameter . . . . .                     | 86"                     |
| Shims . . . . .                             | Circular and<br>Tapered |

## Design Problems

While the Oak Ridge cyclotron belongs to a class which has had twenty years of testing and experience behind it, there are actually some very serious new problems which must be solved before the desired performance of this machine can be obtained. To mention a few of these:

(1) Due to the effect of relativity which is of course by no means negligible, a 2.7% increase in mass will be experienced by the ions. If the ions are to remain within permissible limits of exact resonance, very high dee voltages to ground must be achieved. Such voltages, of the order of 250,000 volts dee to ground, have not yet been applied in vacuum successfully, although at Berkeley 125,000 volts has been obtained. The principle problem seems to be one of supplying the necessary rf power to overcome the losses in the circuit. At the back end of the quarter wave dee lines, the rf current is 5100 amps rms as was mentioned earlier. Even the very small resistance provided will consume 150 kw to obtain 250,000 volts dee-to-ground.

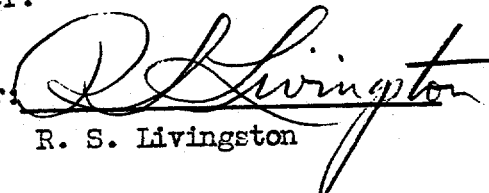
(2) A structure as large and complicated as the dee has not yet been brazed together successfully. The most experienced people in the country are being consulted and the Y-12 shops are doing special investigative work to develop necessary techniques for this work. As an illustration of the type of problem that one may get into, if you attempt to furnace-braze a structure of this size from ordinary copper, some strange things will happen. The copper pieces would be elongated several inches due to oxygen acting as a sort of yeast. However, by using oxygen free high conductivity copper this difficulty may be avoided.

(3)  $10^3$  to  $10^4 \mu\text{a}$  at 25 Mev corresponds to 25 to 250 kilowatts in the ion beam. Impinging this beam on a target without destroying the target presents a severe cooling problem. Such schemes as x-ray type rotating targets will probably be investigated.

(4) If a large number of ions are accelerated for only one or two turns and then lost to the dee walls, a serious drain of rf power will result. Consequently highly efficient ion sources and good initial focusing conditions are essential. For example if the capture efficiency of ions is only one percent and the remaining 99% hit the dee walls with 2500,000 volts one may tabulate the following energy losses:

|     | <u>Ion Beam</u>    | <u>Lost Power</u> |
|-----|--------------------|-------------------|
| for | $10^3 \mu\text{a}$ | 24.7 kw           |
|     | $10^4 \mu\text{a}$ | 247 kw            |

Currently these problems are being investigated on a small test cyclotron in which 2 Mev protons were first produced last October.

Author:   
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